# Reaction Control system Design Considerations for Mars Entry Vehicles

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# Team



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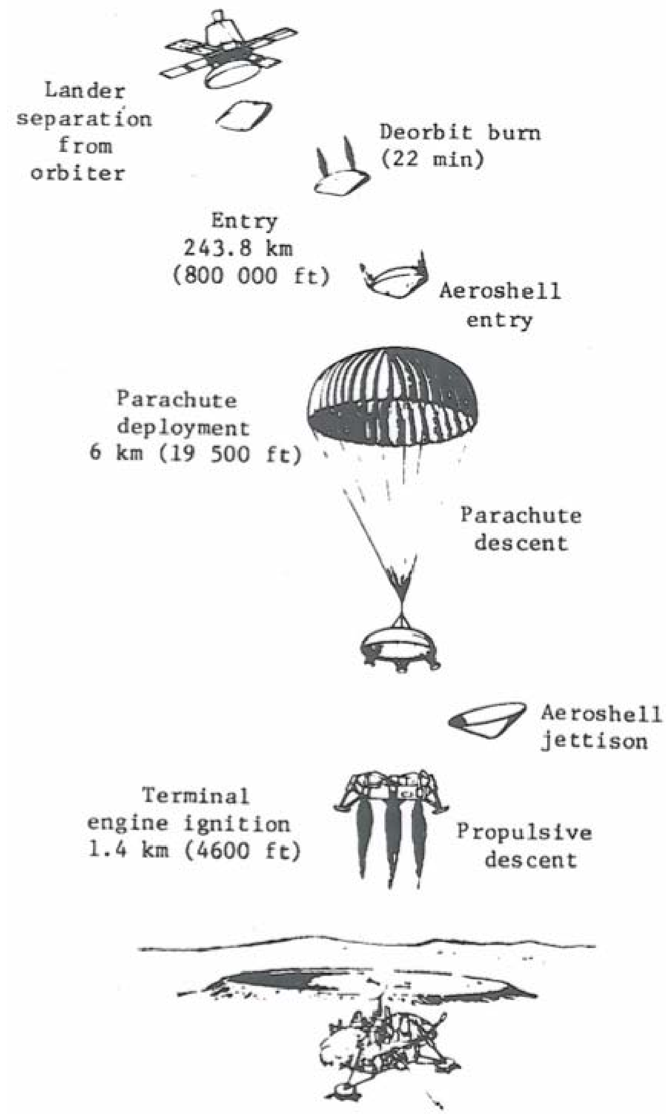
# Overview

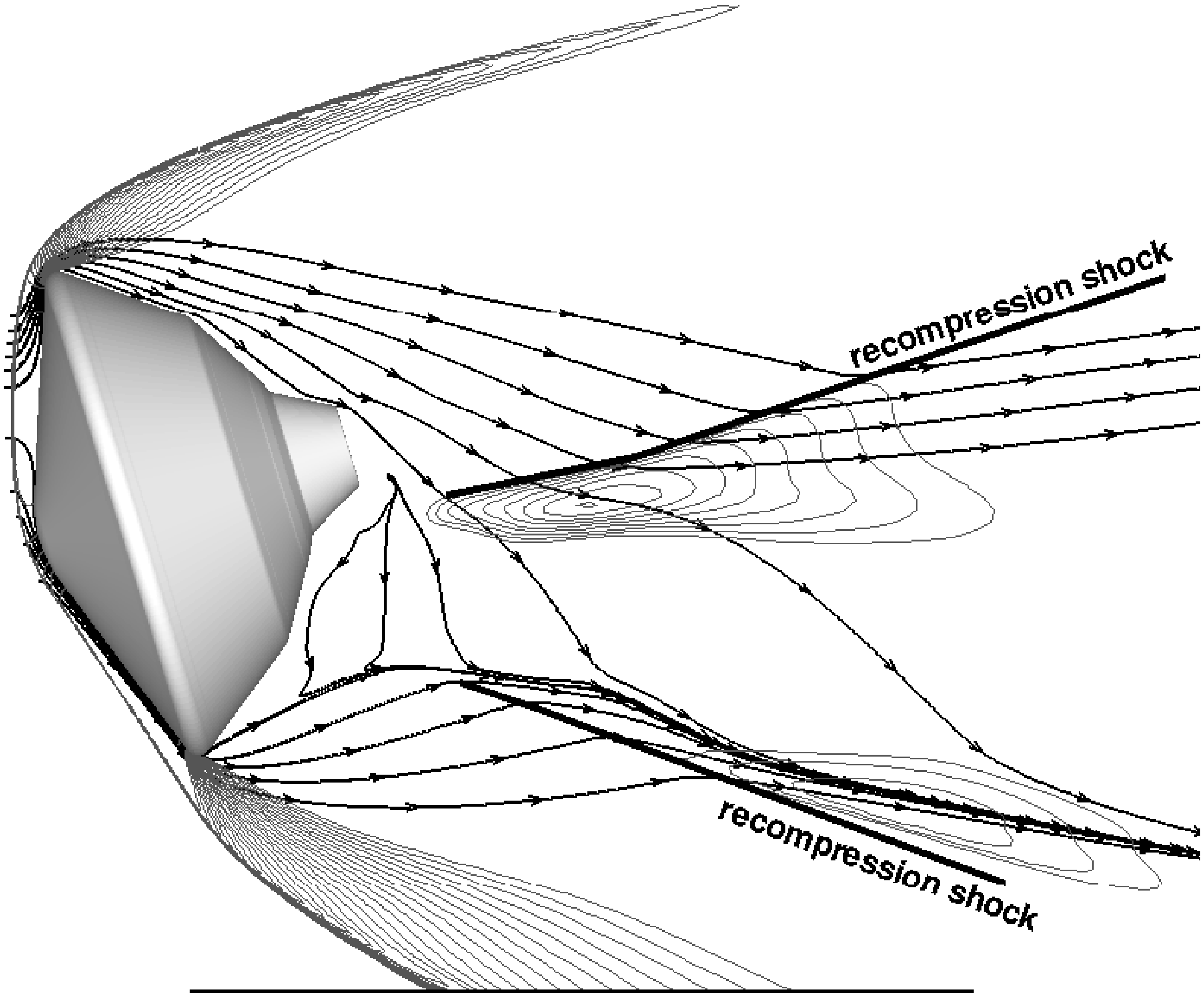
AAD

- Past Mars missions landed within 100s of km from desegnated target
  - Unguided lifting (Viking 1, 2)
  - Unguided ballistic (Pathfinder, MER)
- New generation of Mars landers to deliver massive payloads to within 10s of km from sites of interest
  - Lifting actively guided entry (MSL)
  - High lift-to-drag ratio
- Guided entry requires a reaction control system (RCS)
  - Active control of direction of the lift vector
  - Rate damping
- Guidance maneuvers take advantage of dynamic pressure, so they take place in hypersonic and supersonic segments of the entry
  - Effect of RCS on aerothermal environment can be significant, impacting TPS
  - RCS interference in aerodynamic characteristics neds to be understood to reliably predict flight



# Near-capsule flowfield



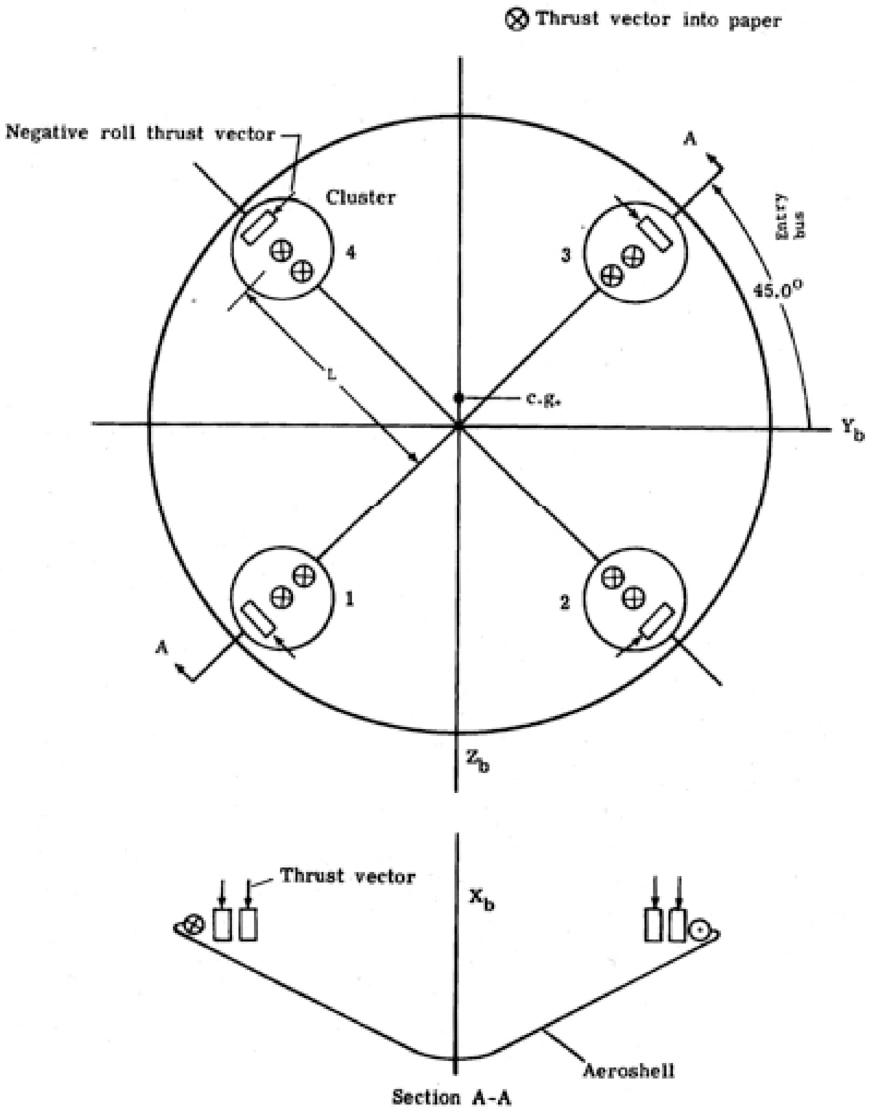



Flow around MSL Capsule at Mach 18.1

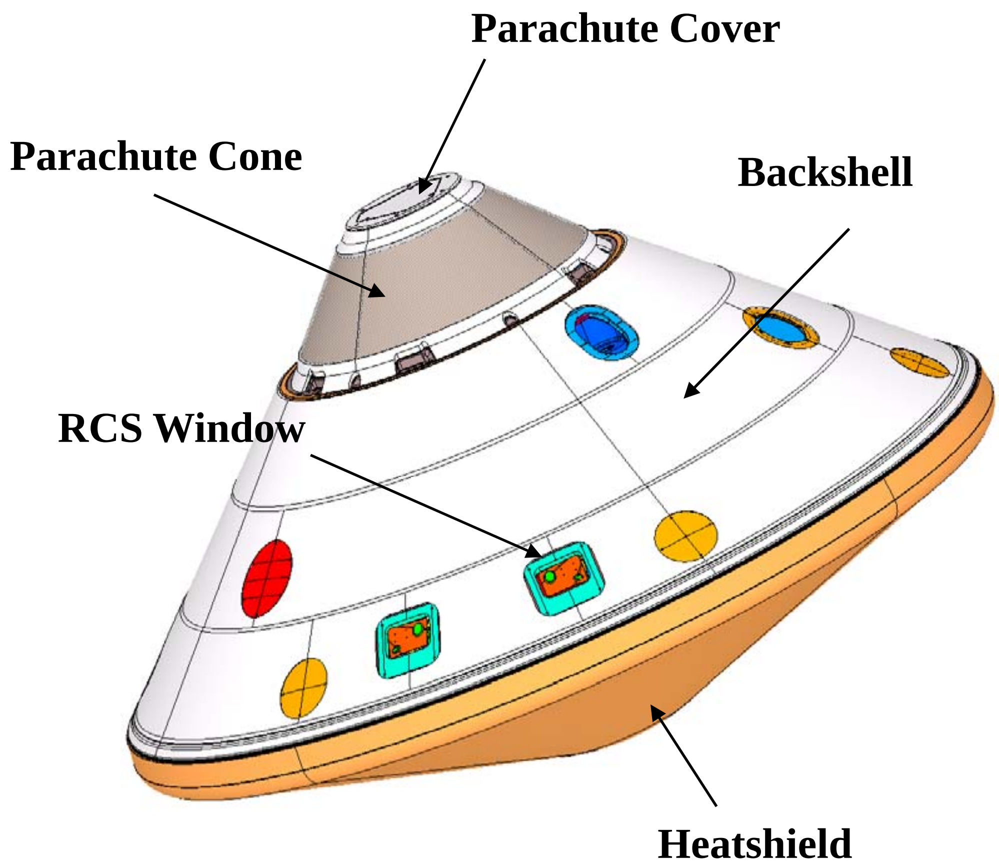
# Reaction Control Systems

AAD

## Viking Lander RCS



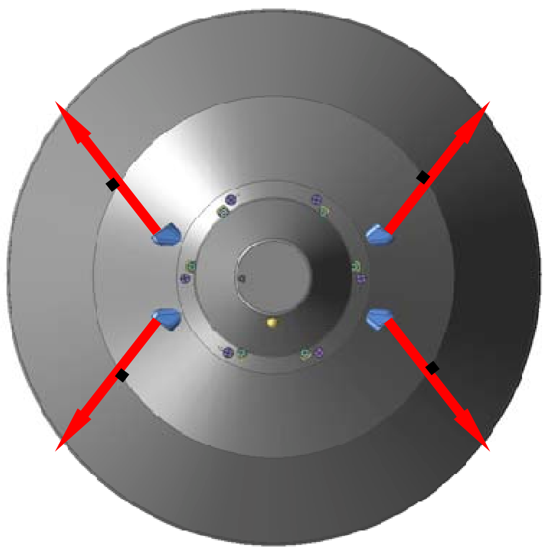

## MPL/Phoenix RCS

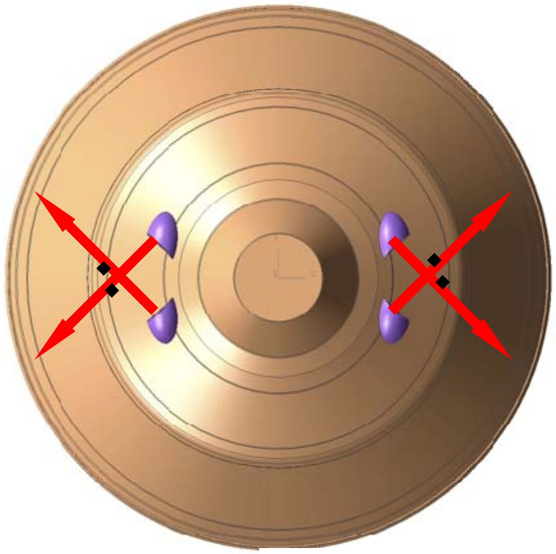


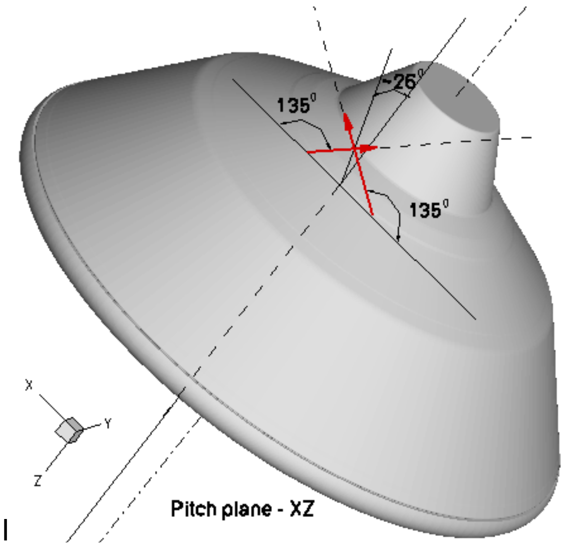
# Reaction Control Systems (cont.)

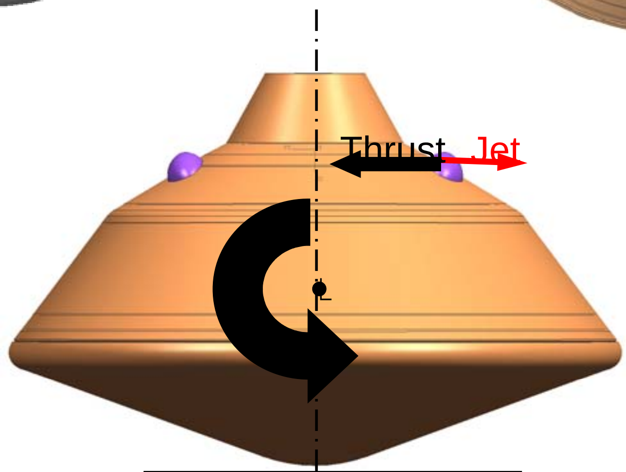


Several Candidate MSL RCS

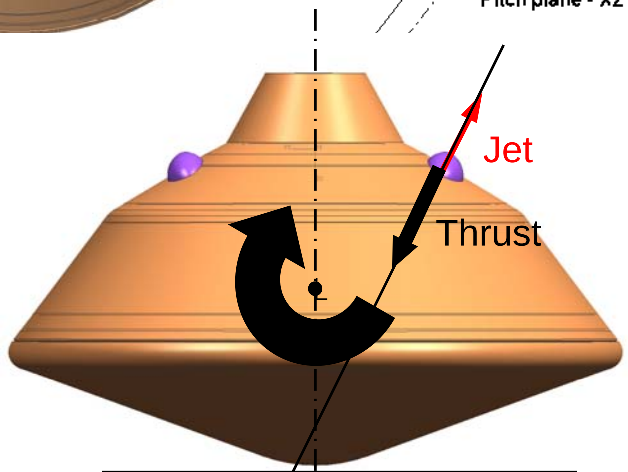







Thust Aft of CG

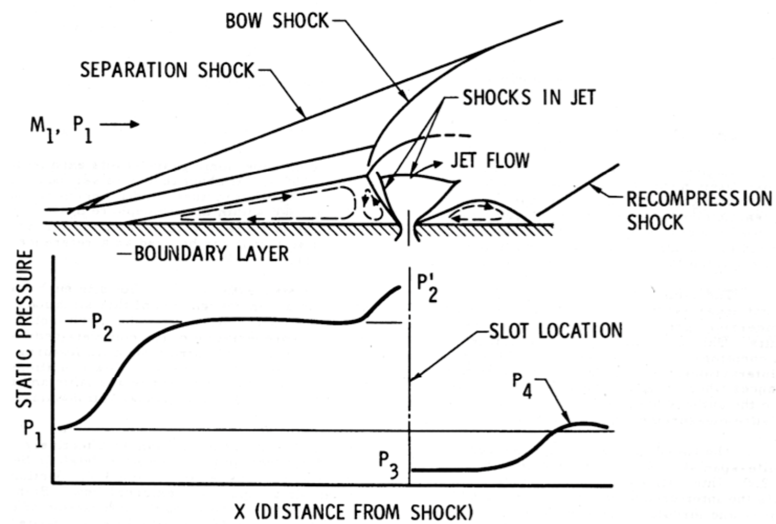



Thrust Ahead of CG

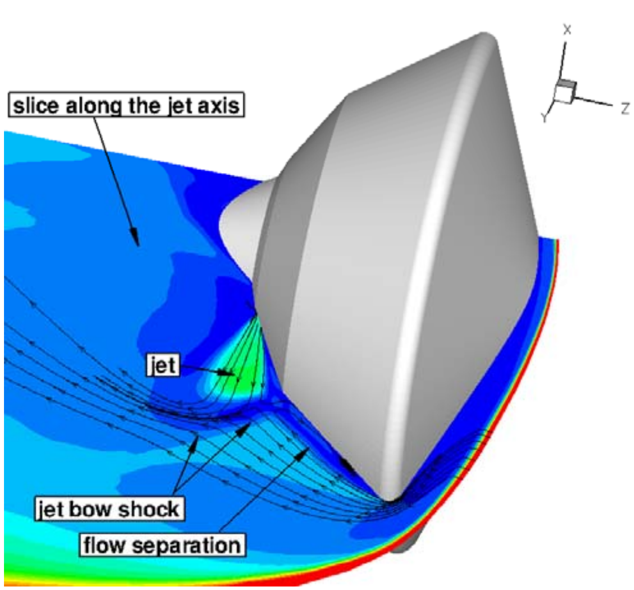
# Jet-Wake Interaction



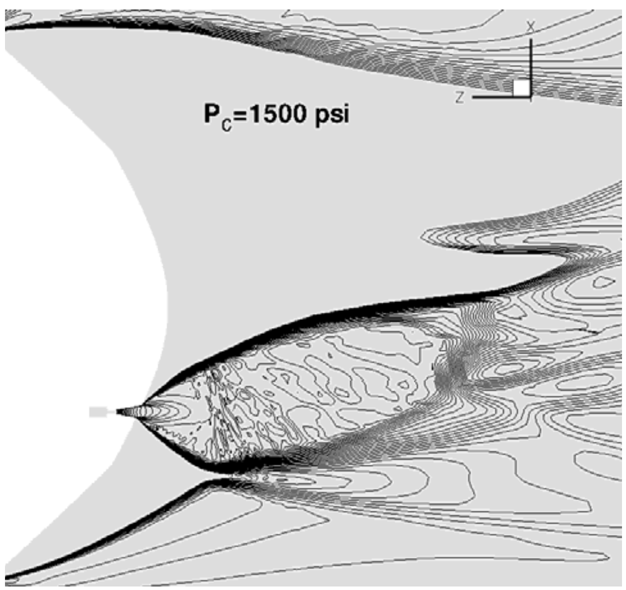
- Interaction of an underexpanded jet with crossflow extensively studied
  - Applicability of existing analyses to scientific planetary entry vehicles is limited
  - Massively separated wake, jet is penetrating flows of changing character
- Analyses and results are configuration specific
  - Interaction with attached vs. separated flow, local flow conditions
  - Pointing of the jet, location on the aftshell



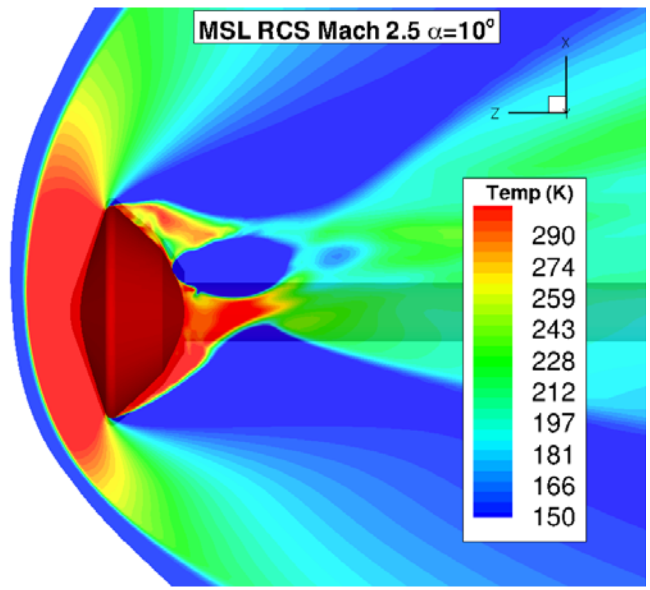

**Interaction with attached flow**




**Interaction with shear layer**




**Interaction with separated flow**



# Aerodynamic Effects



Viking-derived base correction

$$C_{A(base)} = C_{p,b} = a_0 + \frac{a_1}{M_\infty} + \frac{a_2}{M_\infty^2} + \frac{a_3}{M_\infty^3}$$

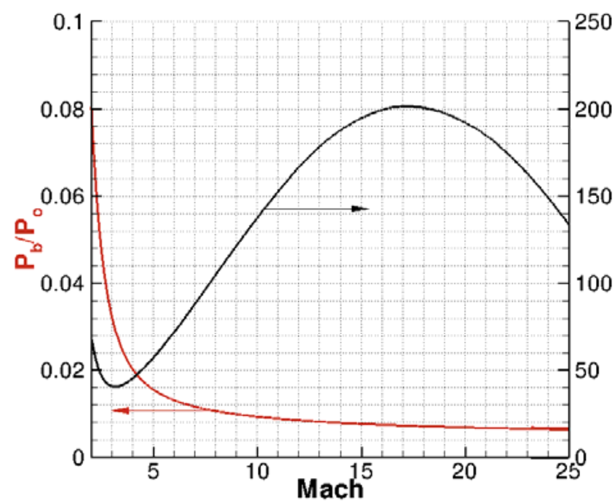
where

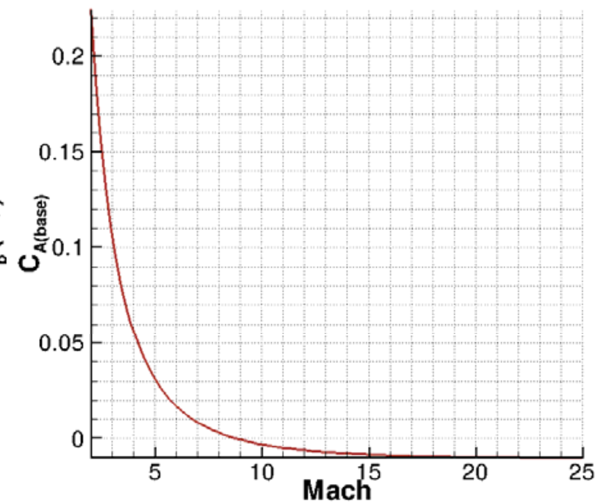
$a_0$ = 8.325E-03

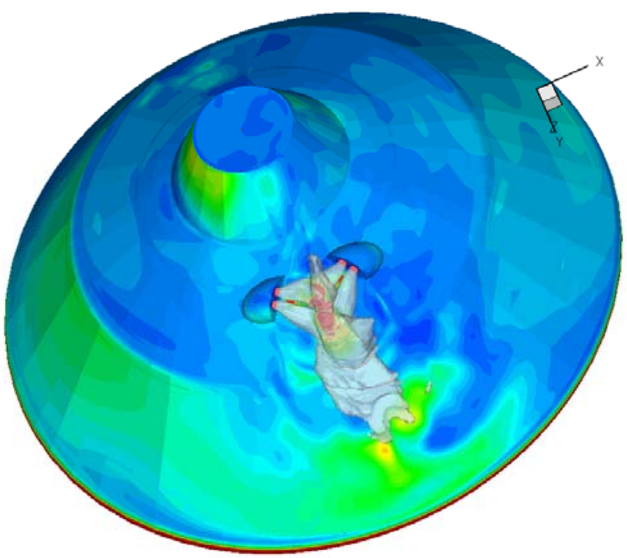
$a_1$ = 1.129E-01

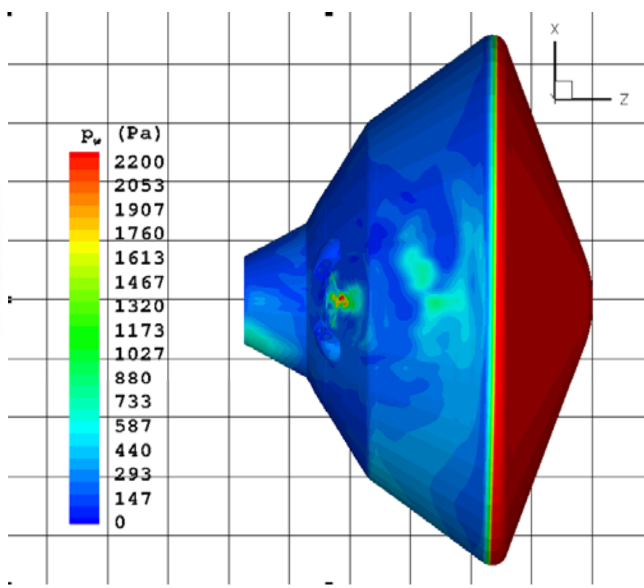
$a_2$ = -1.801E+00

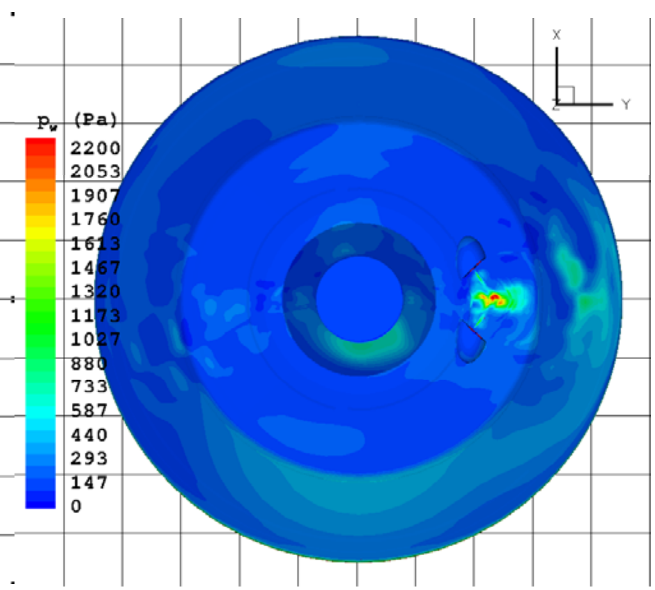
$a_3$ = 1.289E+00



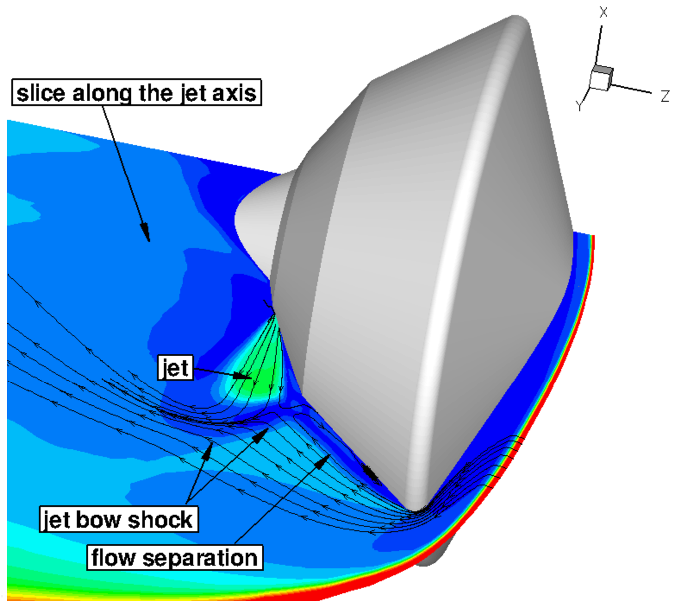



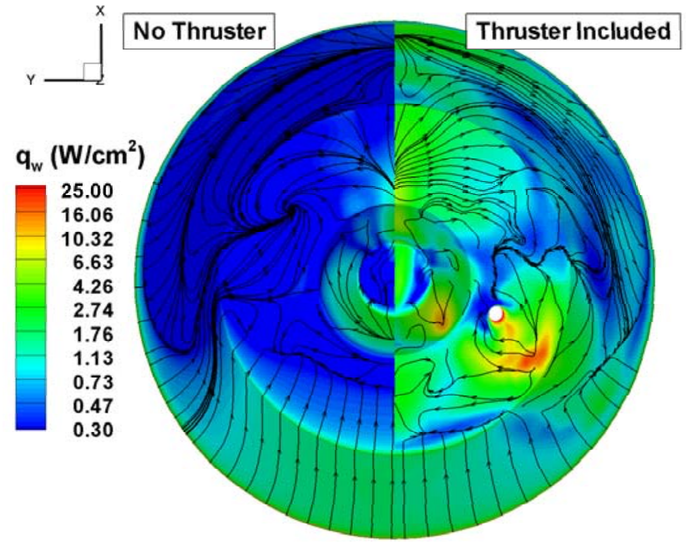


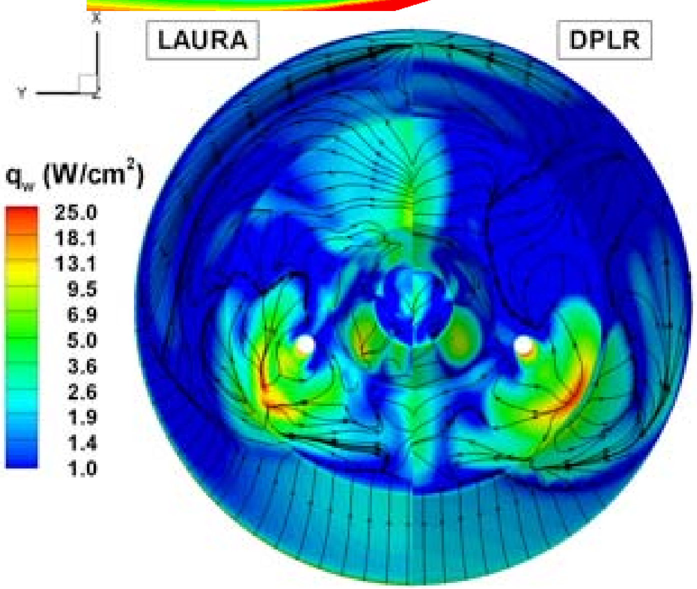



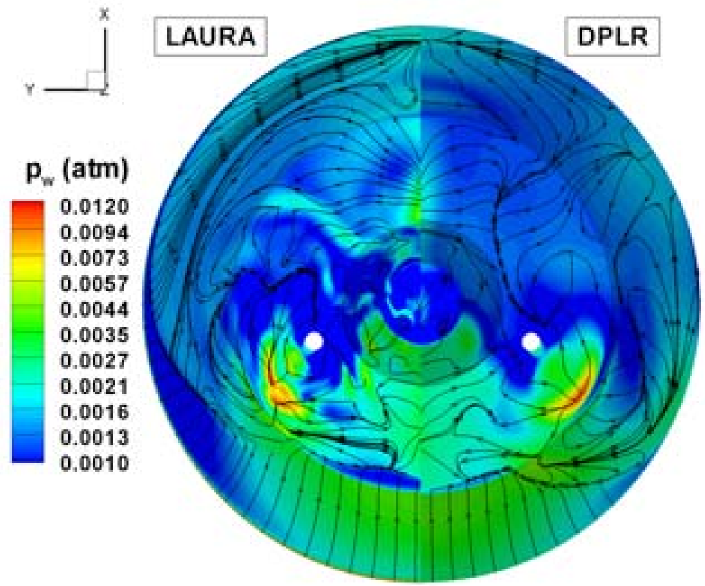
# Aerothermal Effects





# RCS/Gasdynamic Interaction Heritage



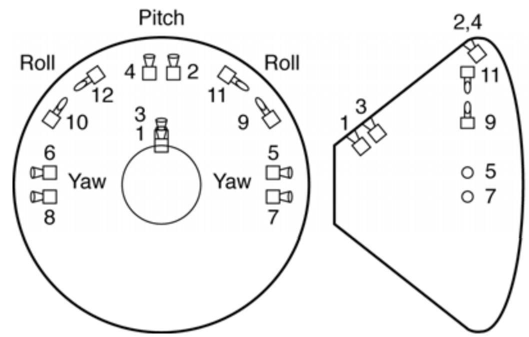
**Apollo**

- Entry Vehicle Control, NASA SP-8028, November 1969.
  - Apollo 7 reentry: “considerable pitch and yaw control activity in the transonic region during the final 2 min before drogue deployment“, from simulation they concluded that this was a result of thruster jet interaction with flow around the vehicle and strong winds.
- NASA TM-X-1063, R. Jones, J. Hunt, Effects of cavities, protuberances, and reaction control jets on heat transfer to the Apollo Command Module
  - Mention of interference patterns on aftbody caused by RCS jets
- NASA TN-D-6028, Dorothy B. Lee, John J. Bertin, Winston D. Goodrich, Heat transfer rate and pressure measurements obtained during Apollo orbital entries
  - Heating on the leeside of the spacecraft increased during RCS firings up to 5 times that measured between firings

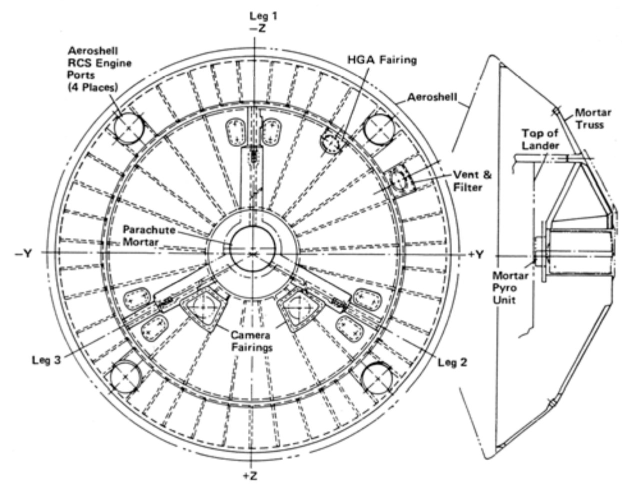
**Viking**

- Blake, W. W., Polutchko, R. J.,”Hypersonic Experimental Aerodynamic Characteristics of Viking Lander Capsule,” Martin Marietta Corporation, TR-3709012, May 8, 1970
  - Aero/RCS interaction estimated in wind tunnel tests at M=20 using solid bodies to represent thruster plumes
  - The data were inconclusive due to insufficient accuracy of the low AOA data
  - The recommendation was use a balance designed to measure small $C_N$ and $C_m$, and large $C_A$ to minimize data uncertainties, but this apparently was never accomplished for Viking

**Apollo**




| Attitude Command | Reaction Jets Fired |
|---|---|
| Pitch down | 2 and 4 |
| Pitch up | 1 and 3 |
| Yaw right | 6 and 8 |
| Yaw left | 5 and 7 |
| Roll left | 10 and 11 |
| Roll right | 9 and 12 |




**Viking**

# Summary



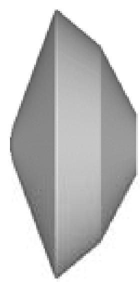
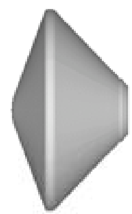
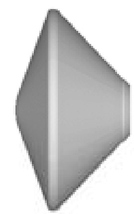
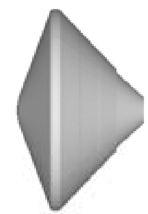
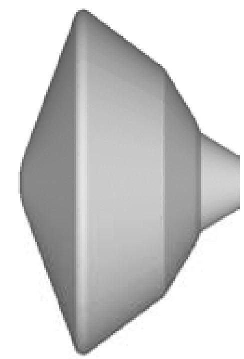
- RCS can interfere  with the aerodynamic characteristics of entry vehicle
  - Changes in aerodynamics occur in both supersonic and hypersonic segments of the entry trajectory
    - Control gain and aerodynamic cross coupling can occur
    - In extreme cases the authority of RCS can be negated
  - Computational and experimental analyses help bound the phenomena
    - Difficulties in both computational methods (wakes are hard to solve) and experiment (moments are small in comparisson to the forebody moments)
- Impact of RCS on aerothermal evironments can be significant
  - Aeroheating increase by an order of magnitude depending on the specifics of the jet interaction
  - Impact on TPS selection, cost, schedule
- Based on analyses performed to date, jet interaction with the flow around entry vehicle is better understood
  - Paradigms have been developed to minimize destructive interference of RCS jets

# BACKUP

# EDL Systems

AAD

**Table 1. Comparison of Mars Entry Capsules**

| | Viking 1/2 | Pathfinder | MER A/B | Phoenix | MSL |
|---|---|---|---|---|---|
| |  |  |  |  |  |
| Diameter, m | 3.5 | 2.65 | 2.65 | 2.65 | 4.5 |
| Entry Mass, kg | 930 | 585 | 840 | 602 | 2919 |
| Landed Mass, kg | 603 | 360 | 539 | 364 | 1541 |
| Landing Altitude, km | -3.5 | -1.5 | -1.3 | -3.5 | +1.0 |
| Landing Ellipse, km | 420 x 200 | 100 x 50 | 80 x 20 | 75 x 20 | < 10 x 10 |
| Relative Entry Vel., km/s | 4.5/4.42 | 7.6 | 5.5 | 5.9 | > 5.5 |
| Relative Entry FPA, deg | -17.6 | -13.8 | -11.5 | -13 | -15.2 |
| $m/(C_D A)$, $kg/m^2$ | 63.7 | 62.3 | 89.8 | 65 | 126 |
| Turbulent at Peak Heating? | No | No | No | No | Yes |
| Peak Heat Flux, $W/cm^2$ | 24 | 115 | 54 | 56 | 243 |
| Hypersonic $\alpha$, deg | -11.2 | 0 | 0 | 0 | -15.5 |
| Hypersonic L/D | 0.18 | 0 | 0 | 0 | 0.24 |
| Control | 3-axis | Spinning | Spinning | 3-axis | 3-axis |
| Guidance | No | No | No | No | Yes |

# Ideal Authority



Table 2. Comparison of ideal authority of Viking, MPL/Phoenix and MSL

| | N-m | | | Kg-m$^2$ | | | deg/sec$^2$ | | |
|---|---|---|---|---|---|---|---|---|---|
| | $M_X$ | $M_Y$ | $M_Z$ | $I_{XX}$ | $I_{YY}$ | $I_{ZZ}$ | $\alpha_X$ | $\alpha_Y$ | $\alpha_Z$ |
| **Viking 1, 2** | 152.7 | 146/-159.4 | 108 | 536 | 423 | 786 | 16.3 | 19.8/-21.6 | 7.9 |
| **MPL/Phoenix** | 10.7 | 58.07 | 10.06 | 192 | 189 | 286 | 3.2 | 17.6 | 2 |
| **MSL** | 675.4 | 980.7/-1160 | 705 | 3055 | 3952 | 4836 | 12.7 | 14.2/-16.8 | 8.4 |

# EDL Sequence

AAD

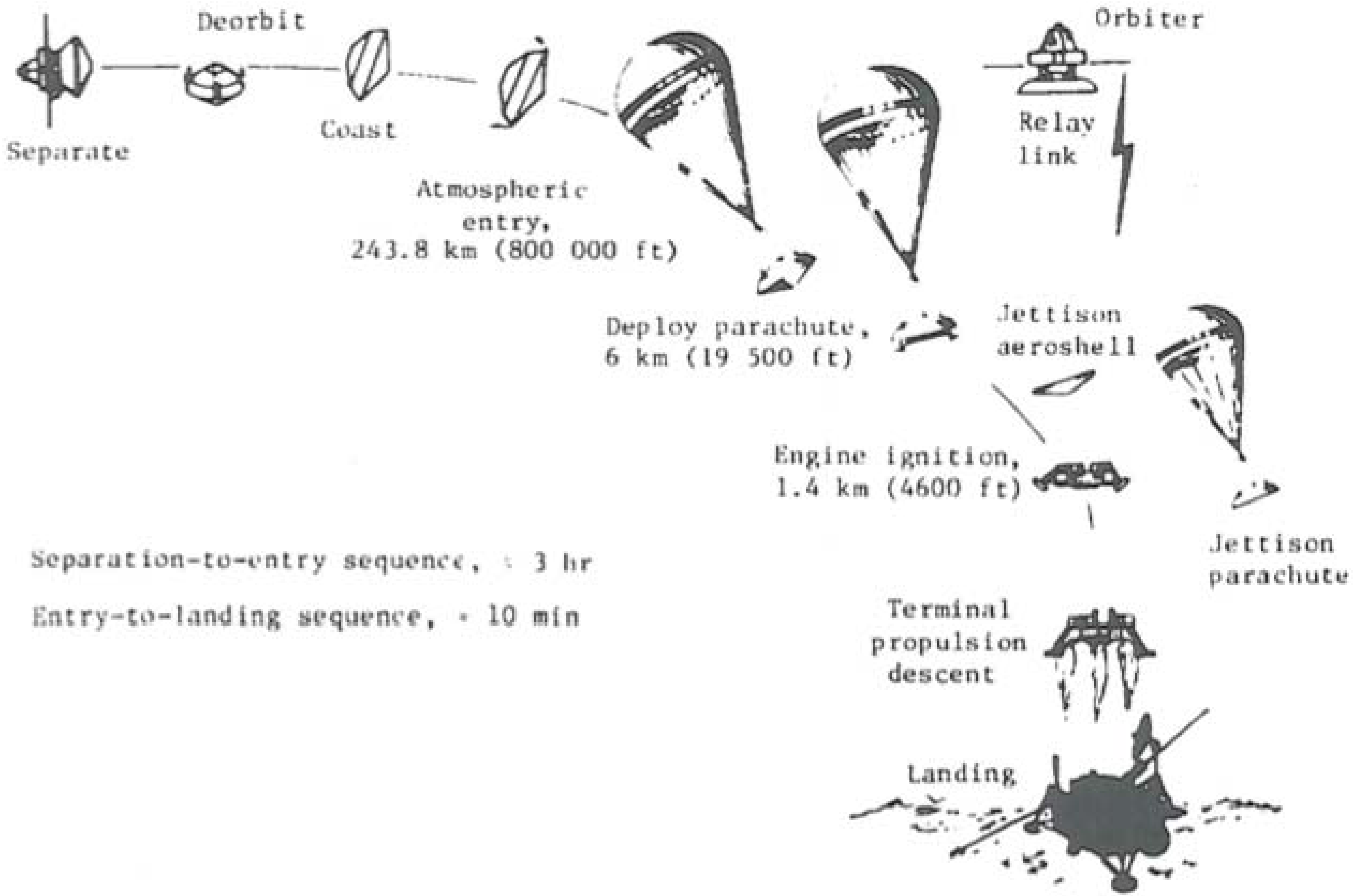
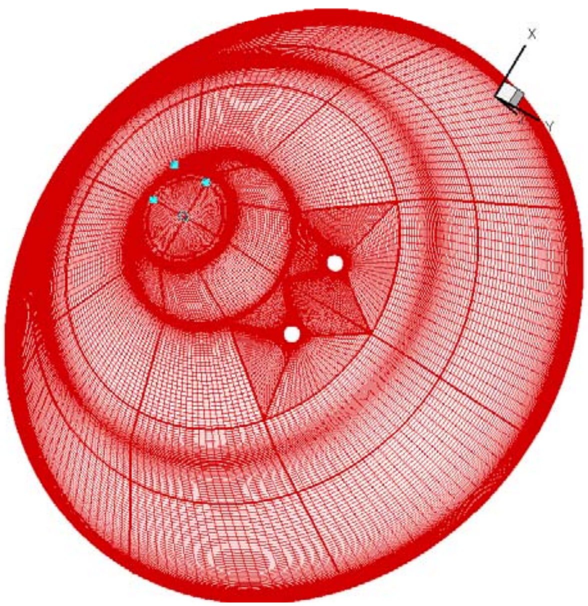
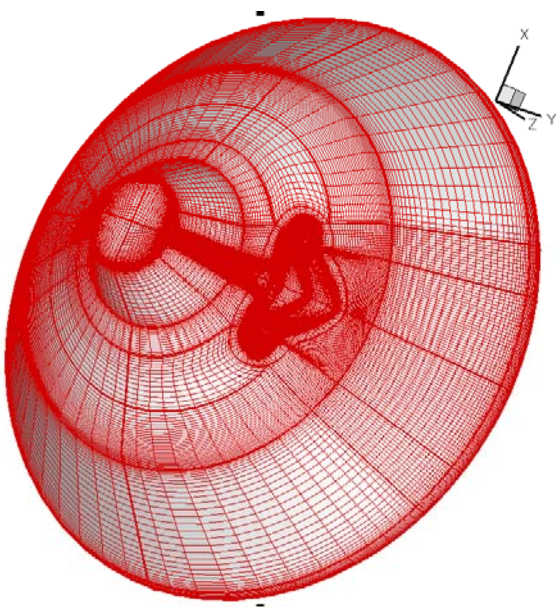
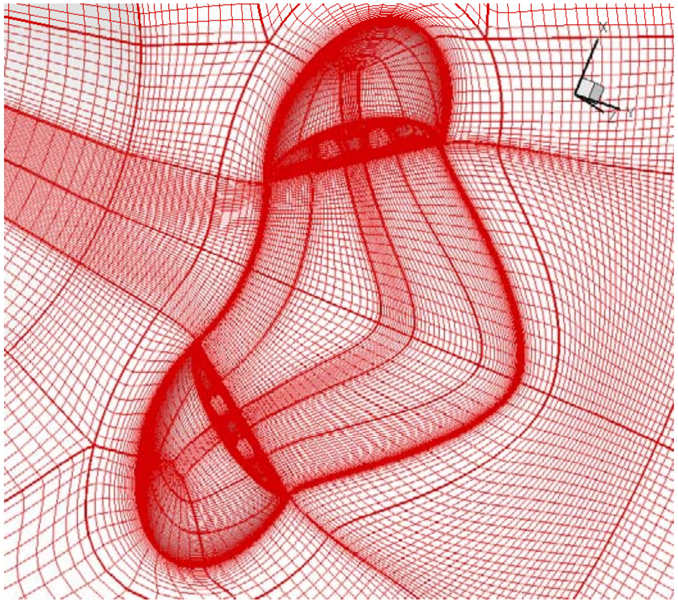



Image courtesy ….

# Algorithm/Grids



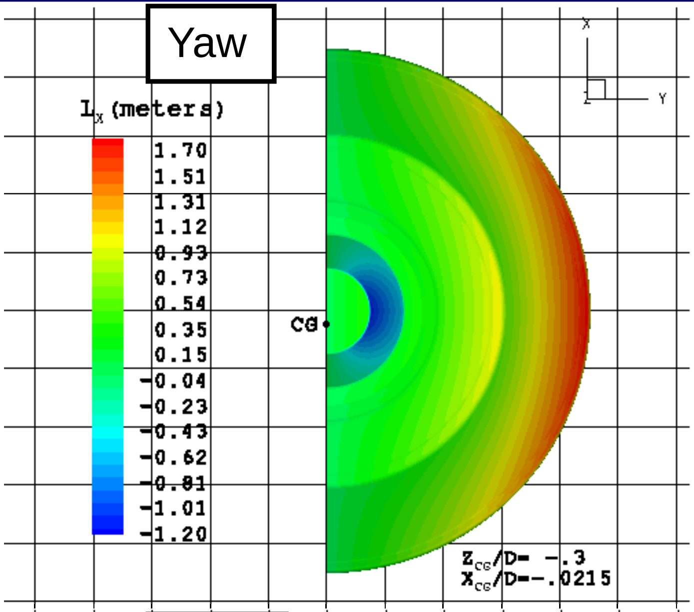
- Calculations in LAURA using 8-species Mars gas + ammonia as propellant
- Grids
  - Baseline layout: coarse - 5M, fine - 40 M nodes
    - Created by Victor Lessard, extends to engine chambers
  - 2006 RCS and Proposed layout - 12M nodes
    - Created using RTF MORPH tool and doesn't reflect any internal flow
- Solutions are computed at Mach 18.1, q=15.9 kPa

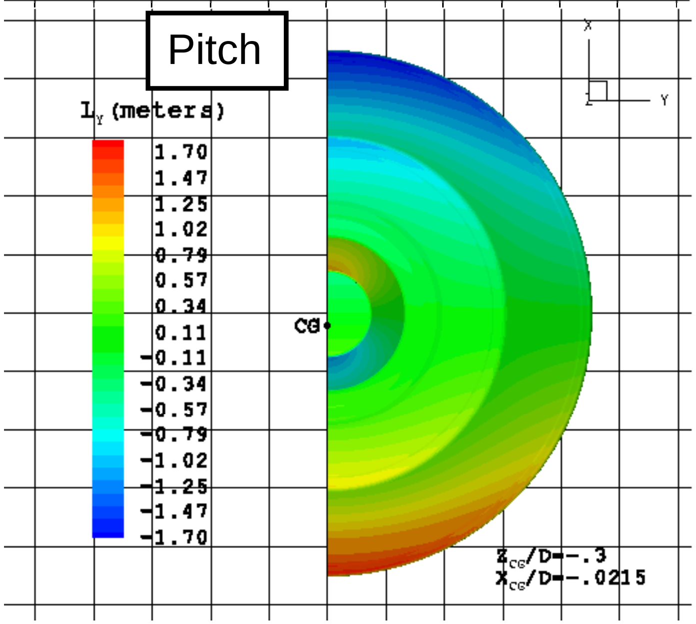




# Geometric Considerations

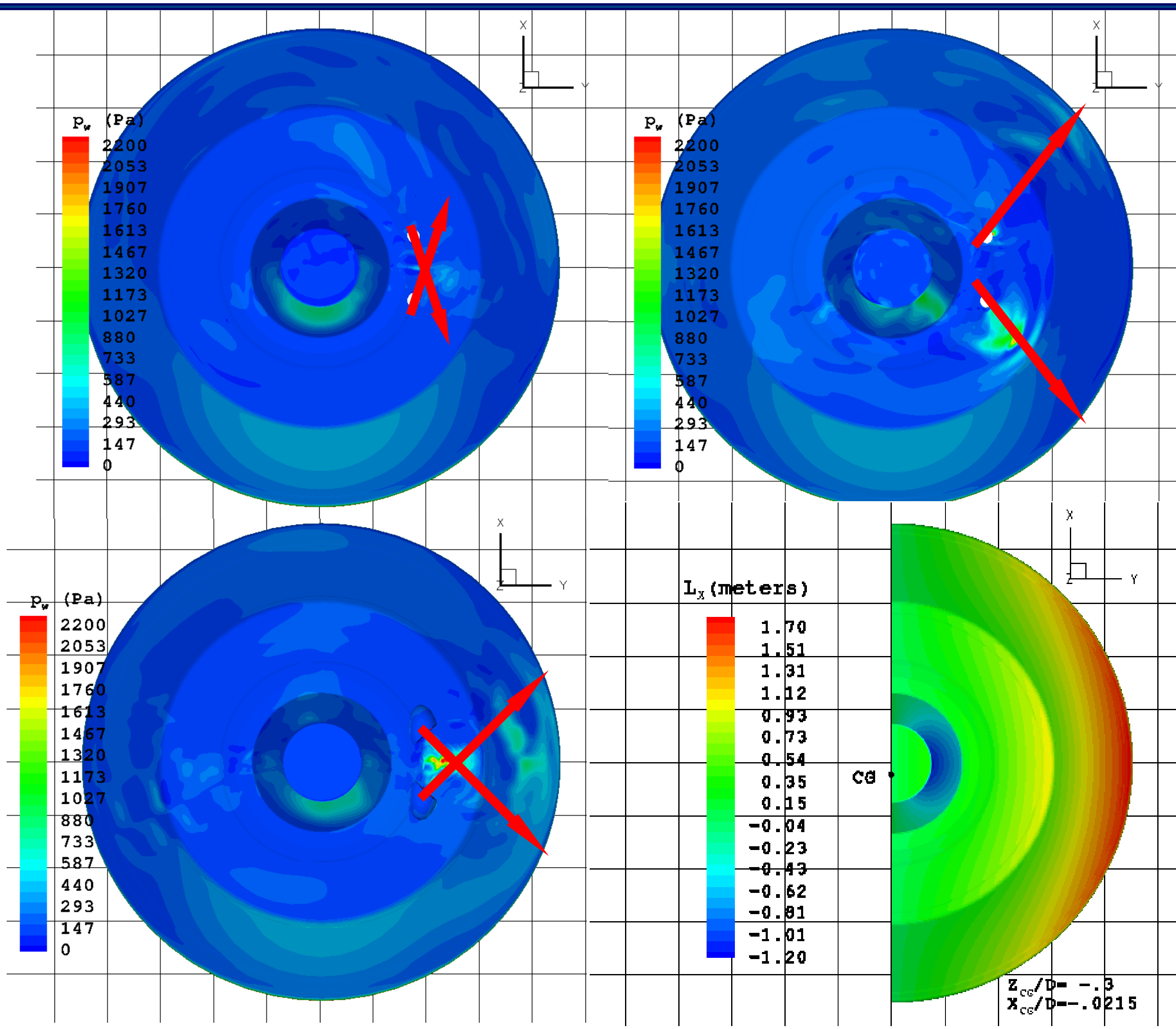
AAD

- Same amount of pressure applied to different locations on the backshell wil produce different moments about the CG
- Moment arms ($L_X$, $L_Y$), computed from a surface-normal through a point and the location of the CG illustrate the regions of high sensitivity of capsule moments to changes in surface pressure
  - In yaw, capsule moments are very sensitive to change in pressure on the far side, and on the parachute closeout cone
  - In pitch, capsule moments are very sensitive to changes in wind/lee shoulder regions; the parachute closeout cone can also generate significant torques if shocks/plumes impinge on it



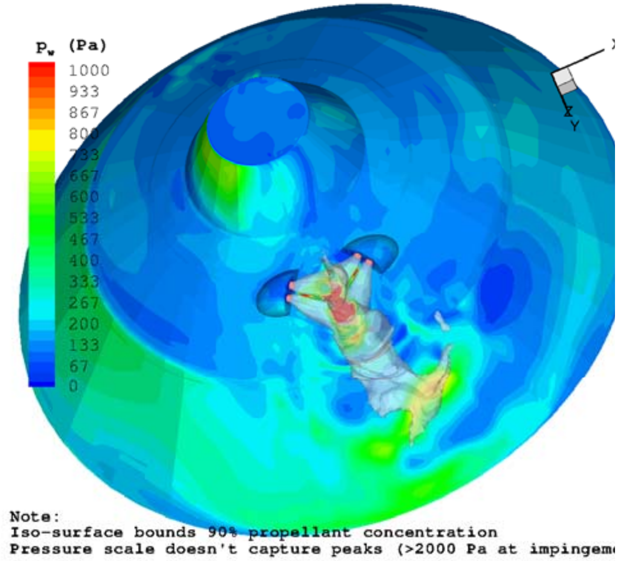



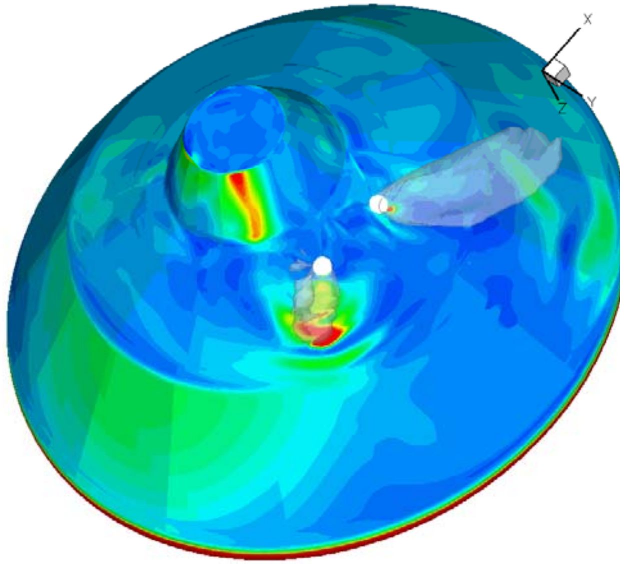
# Backshell Pressures

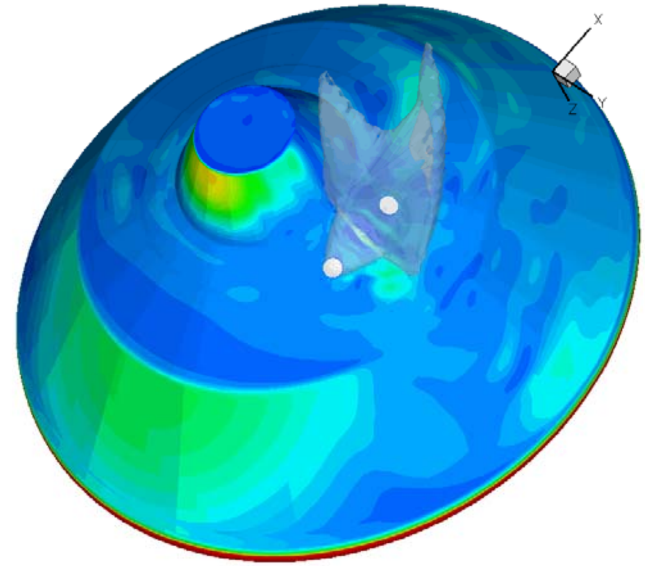


# RCS Plumes of Candidate MSL RCS

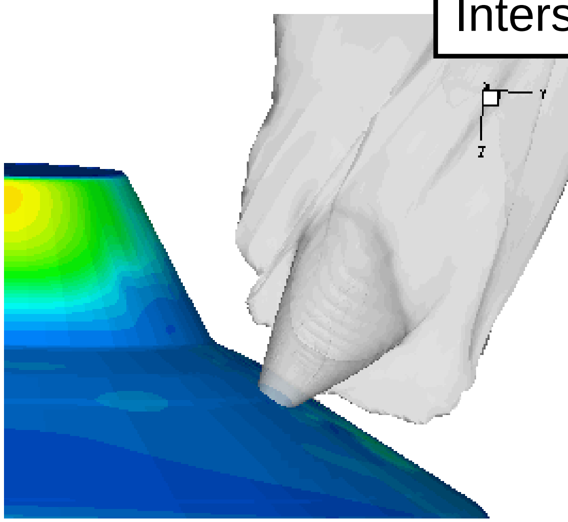


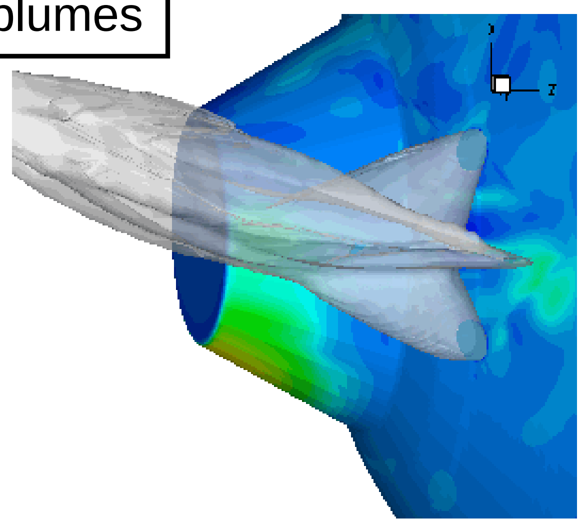




Intersecting plumes





# Backshell Heating